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Errors in Shunt Calibration of Strain Gauge Circuits due to Cable Resistance

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Executive Summary

Strain gauge installations in naval vessels require long cable lengths between strain gauge sites and the strain measuring instrumentation due to the size of the vessels and the complexity of the cable runs. The resistance of the signal cable can cause an attenuation error during the acquisition of strain data. This error can be compensated for by performing a shunt calibration directly on each active strain gauge. However often the strain gauges are inaccessible after installation, in which case the shunt calibration is performed at another part of the Wheatstone bridge or at the instrumentation. The long cable runs can also cause errors in the calibration if it is not undertaken across the strain gauge. The attenuation errors and the calibration errors are additive and in a typical naval vessel installation can result in a total error of up to 20% of the strain signal.

This paper contains derivations of exact formulae for the correction of these errors for various wiring configurations. The more complex formulae were simplified by practical approximations but still retained an accuracy of at least 99% of the exact solutions. It has also been mathematically demonstrated that the use of higher resistance strain gauges reduces the strain errors due to cable resistance. The derived theoretical solutions have been verified by practical experiments for some of the wiring configurations

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He commenced his employment at AMRL in 1991, joining the Specialised Instrumentation Group to assist in the development of the group's capability in sensors and data acquisition. He has been involved in the planning and undertaking of many field and sea trials. He was also involved in the finite element modelling of GRP ship structures, and more recently research into surface ship structures.

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Contents

Notation

F_g = Gauge factor
I_t = excitation current
K = variable used to simplify equation
R_1, R_2, R_3, R_4, = Gauge or precision resistor resistance. Numbering from 1 to 4 represents the four arms of the Wheatstone bridge in which the resistor or gauge is placed.
R_g, R = gauge resistance
R_c = Shunt calibration resistance
R_{cal} = Shunt calibration resistance of a nominal value.
R_L = Resistance in the signal cable between Wheatstone bridge and instrumentation.
R_w = Resistance in the signal cable between gauge and Wheatstone bridge connection.
V_o = Wheatstone bridge output voltage
V_1, V_2, V_3, V_4, = Voltage potential at nominated locations.
V_S = Wheatstone bridge excitation consisting of positive voltage on one side and zero voltage on other side of the bridge.
ε = Strain
ε_c = Equivalent nominal calibration strain
ε_{cal} = Equivalent calibration strain
δ_{att} = attenuation error
δ_{cal} = shunt calibration error
δ_T = Summation of attenuation and shunt calibration error

1. Introduction

When conducting strain measurements, the acquisition instrumentation is often located some distance from the strain gauges particularly when large structures such as naval or commercial vessels are being monitored. This requirement may be due to any number of reasons, including environmental, spatial and economical considerations, ie. potential location could be considered hostile to instrumentation or inaccessible, or merely the requirement for easy access and need for the instrumentation to be centrally located.

Strain gauge circuits are usually connected in a constant voltage Wheatstone bridge configuration comprising of one, two or four active gauges depending on measurement requirements. The remaining elements of the Wheatstone bridge are usually completed with precision resistors.

There are various types of errors that occur when long leads are used between the strain gauge and the instrumentation. These include attenuation due to long leads between the gauge and the Wheatstone bridge, attenuation due to long leads between the Wheatstone bridge and the instrumentation and calibration errors when shunt calibration is undertaken at the instrumentation or Wheatstone bridge.

The theory covered in this paper covers case combinations where long leads have been used between the gauge and the Wheatstone bridge. This study has been restricted, for ease of explanation, to quarter-bridge (one active strain gauge within the Wheatstone bridge) and half bridge configurations (two strain gauges within adjacent arms of the bridge). Never the less, the equations derived in this paper to calculate the error due to long wires within a half bridge configuration can easily be used to cover a full bridge configuration. For the half bridge, this paper addresses configurations where three wires (commonly called three wire method) and four wires (commonly called four wire method) are used to connect the two gauges into the Wheatstone bridge.

This paper also derives signal attenuation and calibration error equations where the strain gauges and precision resistors are connected to form a Wheatstone bridge with short bridge wires, but a long signal cable has been used to connect the bridge to the instrumentation. Experimentation was carried out to verify some of the derived equations.

2. Definition of a Wheatstone Bridge

A Wheatstone bridge is defined as four resistors or strain gauges, connected in such a way that it forms a closed loop with four connection points (See Figure 1a). Excitation voltage is connected to two opposite points of connection (supply wires), and output wires (signal wires) are connected to the other two. In practice, these points of

connection usually occur on a terminal block or junction box, especially if a large number of locations are being measured. Note that it is the physical location of these four connections and not the physical location of the resistors/strain gauges that defines the location of the Wheatstone bridge.

For clarification, throughout this paper the term *bridge wire* will be used to describe the connecting wires between the strain gauges or resistors to the connection point to form the Wheatstone bridge; the term *signal wire* to describe the wires from the recording instrumentation to the Wheatstone bridge; the term *supply wire* to describe the wires from the supply voltage of the instrumentation to the Wheatstone bridge. As the latter two usually consists of a single four-core cable, the combined will be described as *signal cable*.

The common type of bridge configurations are shown below:

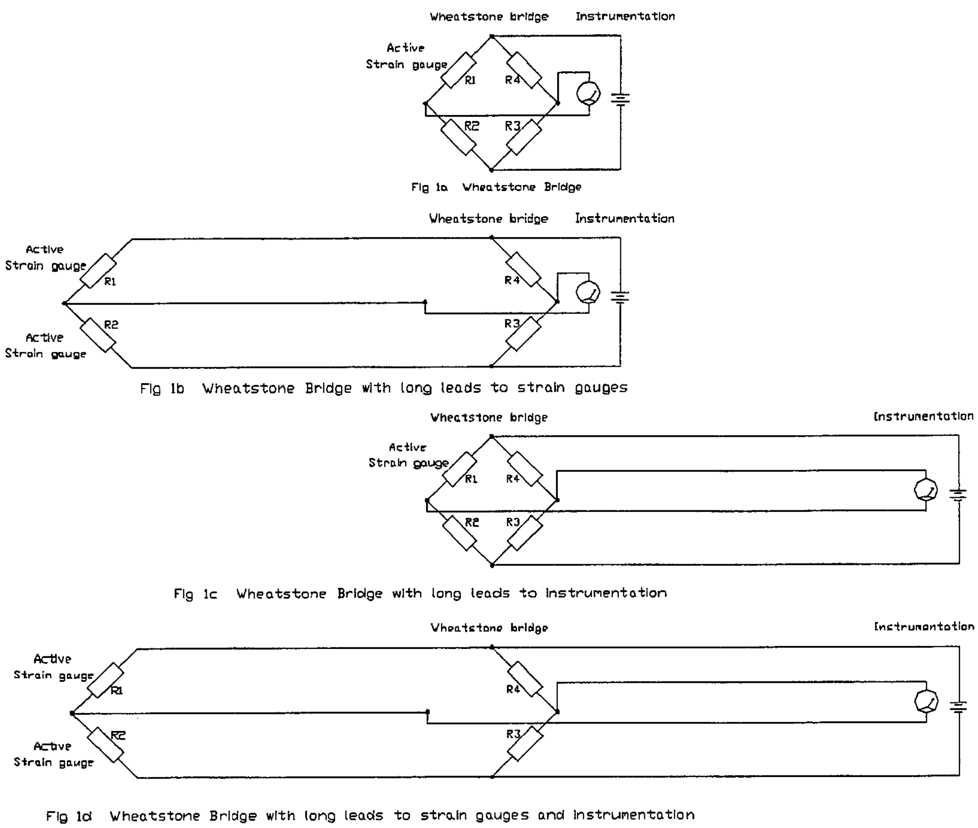

Figure 1. *Some of the various wiring configurations available when using a Wheatstone bridge.*

Figure 1 shows a typical Wheatstone bridge configuration with one active strain gauge and completed with resistors of equal value. Figure 1b shows a Wheatstone bridge with two strain gauges at a location that is some distance from the Wheatstone bridge connection point. Figure 1c shows a Wheatstone bridge with the instrumentation at a location that is some distance from the bridge. Figure 1d is a combination of Figure 1b and 1c adding additional complexity.

3. Output Error Due to Long Cables between the Strain Gauge and the Wheatstone Bridge.

3.1 Attenuation Due to Long Bridge Wires

One type of inherent error associated with strain measurement is due to the use of long cable lengths between the Wheatstone bridge and the strain gauges. The error arises from the resistance in the cables causing attenuation of the magnitude of the signal output. The attenuation of a strain gauge signal will occur when there is lead-wire resistance in series with the strain gauge and the Wheatstone bridge (ie. resistance in the bridge wires). As the attenuation is a function of the length of the bridge wires that connect the gauges into a Wheatstone bridge, it will have greater effect with increasing cable length. As the theory of attenuation is well documented in Dally, James &Riley (1978), Murray and Miller (1992) et al, it will not be covered here. For convenience, the equations for calculating the attenuating error are reproduced for a three and four wire configuration.

For a three wire configuration:

$$\%\delta_{att} = \frac{R_w}{R_g + R_w} \times 100 \tag{1}$$

For a four wire configuration:

$$\%\delta_{att} = \frac{2R_w}{R_g + 2R_w} \times 100 \tag{2}$$

where R_g = gauge resistance
R_w = Resistance in the lead-wire
δ_{att} = attenuation error

From equations 1 and 2, it can be seen that attenuation error for a four-wire configuration is *approximately* double that of the three-wire configuration.

This error can sometimes be overcome by calibration. Calibration of strain gauge circuits is commonly accomplished by connecting a known precision resistance in parallel with one element of the Wheatstone bridge. This method, known as "shunt calibration" simulates a compressive strain in that arm of the Wheatstone bridge,

which enables the equivalent strain to be calculated. Thus entire strain gauge circuit including the instrumentation is calibrated using this method. If shunt calibration is carried out at the active gauge, the attenuation error will be automatically compensated for in the circuit sensitivity value derived from the shunt calibration. In most cases the active gauge is not accessible, thus the need for an accurate calculated correction factor to compensate for the attenuated signal.

3.2 Shunt Calibration (General Theory)

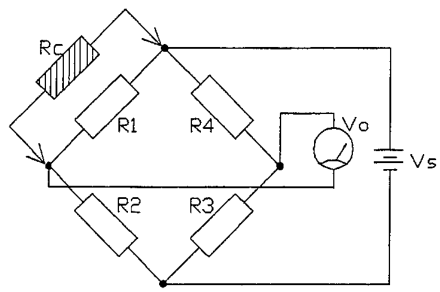

Figure 2. Shunt calibration of a single gauge in a Wheatstone bridge (quarter, half or full bridge configuration)

The formula for calculating the equivalent strain generated by a shunt calibration resistor placed across an arm of the Wheatstone bridge (as in Figure 2) can be derived from the following basic definition of gauge factor (Perry & Lissner 1955):

$$\frac{\Delta R}{R} = F_g \varepsilon \qquad (3)$$

where R = Gauge resistance
F_g = Gauge factor
ε = Strain

When the shunt calibration resistor is connected, the change in resistance is equal to:
$\Delta R = R_1 - R_1 \| R_c$.
Therefore equation 3 becomes:

$$F_g \varepsilon_c = \frac{R_1 - \left(\frac{R_1 \times R_C}{R_1 + R_C}\right)}{R_1}$$

$$\varepsilon_c = \frac{R_1}{F_g (R_1 + R_C)} \qquad (4)$$

where ε_c = Equivalent nominal calibration strain

R_1 = Nominal gauge resistance eg. 120Ω, 350Ω or 1000Ω.
R_c = Shunt calibration resistance

Equation 4 is the basic formula used by strain gauge manufacturers when calculating nominal values for the manufacture of calibration resistors. Typical commercially available shunt calibration resistor values are shown in Table 1. The values are derived from the nominal strain gauge resistance (120, 350, or 1000Ω), and for a gauge factor of 2.0.

Table 1: *Nominal Shunt calibration resistor values. (Measurements Group 1988)*

Equivalent Micro-strain (με)	120Ω nominal Resistance in ohms	350Ω nominal Resistance in ohms	1000Ω nominal Resistance in ohms
500	119880	349650	999000
1000	59880	174650	499000
2000	29880	87150	249000
3000	19880	57983	165666
4000	14880	43400	124000
5000	11880	34650	99000
10000	5880	17150	49000

3.3 Shunt Calibration Error Due To Cable Resistance

The cable resistances in the strain gauge circuit can not only attenuate the output signal, it can also introduce a second error when a shunt calibration is undertaken. This error will alter the calibration sensitivity in such a way that when strain output is calculated from the output voltage and the calibrated sensitivity, the output strain will be lower then the actual strain. However, if a correction formula is used, then this output could then be corrected to compensate for the attenuated signal.

A Technical note by Measurements Group (1988) discusses shunt calibration and associated calibration errors. The paper recommends various shunt calibration techniques for the various configurations, and derives appropriate shunt calibration error corrections when strain gauges are required to be positioned at locations remote to the instrumentation. However, Measurements Group (1988) does not cover the type of shunt calibration errors discussed in this paper but recommends that additional lead-wires should be installed from the gauge site to the instrumentation specifically for calibration purposes to overcome these errors. Murray and Miller (1992) also recommend this, however, this is not always practical as it is neither cost effective nor time efficient. To the authors' knowledge, there is no documentation that fully covers the types of shunt calibration errors addressed by this paper.

As discussed, if strain gauges are located such that long bridge wires are required to connect them into the Wheatstone bridge, then errors can occur in the calibration

process. These errors can be avoided if calibration occurs at the active gauge site. However, this is not always possible. In many situations the gauges are not accessible, are covered with a protective coating, or in cases where gauges have been installed in many locations, the calibration process at individual sites would be very time consuming.

Shunt calibration for a half bridge configuration in theory can be carried out across the precision resistors instead of the strain gauges without incurring any shunt calibration error. This could be used where the precision resistors are accessible and would be convenient if they are located at the instrumentation. (This method would avoid shunt calibration error but not the attenuation error described above.) However, in practice this is not always possible since there are many strain measuring instruments that have half of the Wheatstone bridge built in to the system, and are therefore inaccessible for calibration by this technique. Obviously this is also not possible when a full bridge configuration is being used where four strain gauges complete the Wheatstone bridge. If shunt calibration is required to be carried out then it is important to know the magnitude of the error so that corrections can be applied to the output signal.

3.4 Calculation of Shunt Calibration Error of Half Bridge using the Four Wire Configuration.

This section considers the case where two gauges are placed at a remote location and a long length of four wire signal cable is used to connect the gauges into a Wheatstone bridge configuration (Figure 3). As a single cable has been used, all four bridge wires within the cable are assumed to be of equal length and thus assumed to be of equal resistance (R_w).

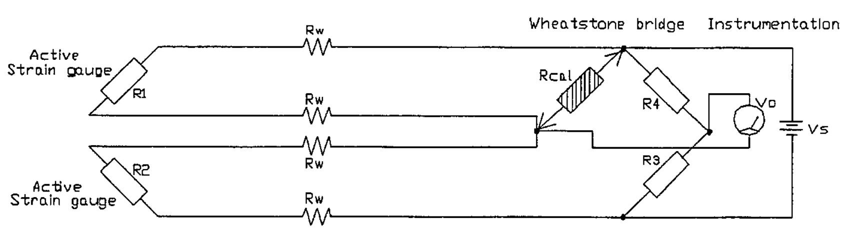

Figure 3. Wheatstone bridge using the four-wire configuration.

The shunt calibration error can be calculated as a function of voltage drop across the bridge output when a shunt calibration resistor is placed across an arm of the Wheatstone bridge. The circuit of the Wheatstone bridge in Figure 3 can be redrawn schematically as shown in Figure 4. Using the voltage divider principle (Jackson 1981), V_1 can be calculated in terms of V_S before and after the calibration resistor is applied. This method assumes the meter resistance approaches infinity.

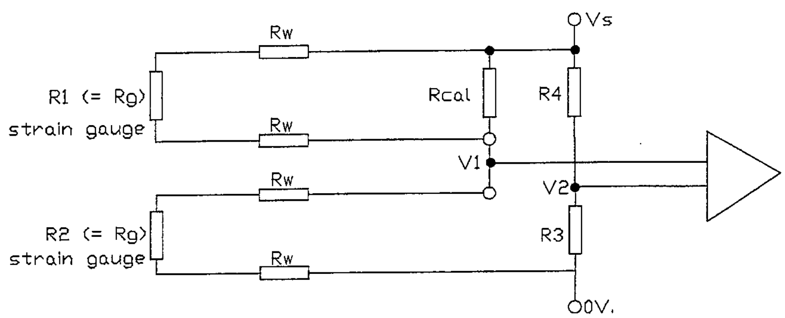

Figure 4. *Equivalent circuit of Wheatstone bridge using the four-wire configuration.*

Before the calibration resistor is placed across the arm of the bridge ($R_{cal} = \infty$) the output from the bridge is equal to:

$$\Delta V = V_1\big|_{Rcal=\infty} - V_2\big|_{Rcal=\infty}$$

$$= \frac{V_s(R_g + 2R_w)}{(R_g + 2R_w) + (R_g + 2R_w)} - \frac{V_s}{2} \qquad (5)$$

$$= \frac{V_s}{2} - \frac{V_s}{2} = 0$$

As $\Delta V = 0$, the Wheatstone bridge is in balance as expected.
Similarly after a calibration resistor is placed across an arm of the Wheatstone bridge, ($R_{cal} \neq \infty$), the output from the bridge is equal to

$$\Delta V = V_1\big|_{Rcal\neq\infty} - V_2\big|_{Rcal=\infty}$$

The voltage at V_1 is given by:

$$V_1\big|_{Rcal\neq\infty} = \frac{V_s(R_g + 2R_w)}{(R_g + 2R_w) + (R_{cal})\|(R_g + 2R_w)}$$

$$= \frac{V_s(R_g + 2R_w + R_{cal})}{(R_g + 2R_w + 2R_{cal})} \qquad (6)$$

The voltage at V_2 is given by:

$$V_2\big|_{Rcal\neq\infty} = \frac{V_s}{2}$$

As voltage at V_2 does not change in both cases, the change in voltage when the calibration resistor is placed across an arm of the bridge can be calculated from:

$$\Delta V = V_1\big|_{Rcal\neq\infty} - V_1\big|_{Rcal\neq\infty}$$

$$= \frac{V_s(R_g + 2R_w + R_{cal})}{(R_g + 2R_w + 2R_{cal})} - \frac{V_s}{2}$$
$$= \frac{V_s(R_g + 2R_w)}{(R_g + 2R_w + 2R_{cal})} \qquad (7)$$

The shunt calibration error due to cable resistance can be calculated from :

$$\%\delta_{cal} = 1 - \frac{\Delta V_1|_{Rw\neq 0}}{\Delta V_1|_{Rw=0}} \times 100 \qquad (8)$$

$$= 1 - \frac{V_s(R_g + 2R_w)}{2(R_g + 2R_w + 2R_{cal})} \div \frac{V_s R_g}{2(R_g + 2R_{cal})} \times 100$$
$$= 1 - \frac{(R_g + 2R_w)(R_g + 2R_{cal})}{R_g(R_g + 2R_w + 2R_{cal})} \times 100 \qquad (9)$$

3.5 Shunt Calibration Error of a Half Bridge using the Three Wire Configuration

This section considers the case where two strain gauges are placed at a remote location and a long length of three core cable is used to connect the gauges into a Wheatstone bridge configuration as shown in Figure 5. As a single cable has been used, the three bridge wires are of equal length, and thus assumed to be of equal resistance (R_w).

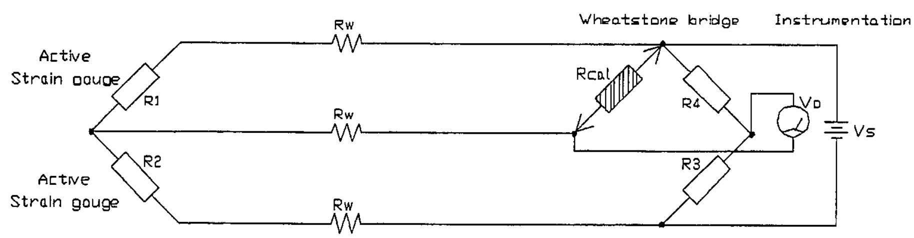

Figure 5. Wheatstone bridge using the three-wire configuration.

The shunt calibration error can be calculated as a function of voltage drop across the meter when a shunt calibration resistor is placed across an arm of the Wheatstone bridge. It is assumed that the Wheatstone bridge is initially balanced and R1 = R2 = R3 = R4 = Rg. The circuit of the Wheatstone bridge in Figure 5 can be redrawn schematically as shown in Figure 6.

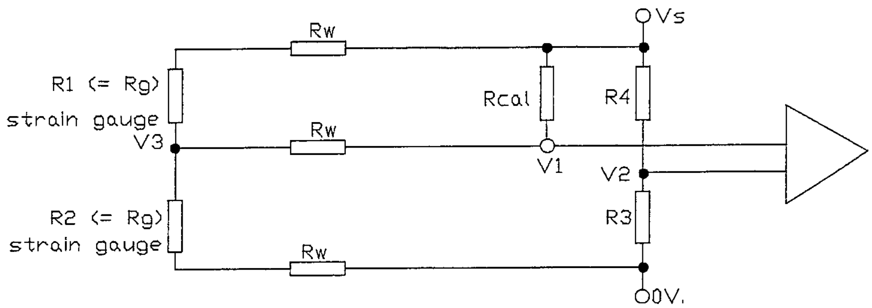

Figure 6. *Equivalent circuit of Wheatstone bridge using the three-wire configuration.*

This method assumes the meter resistance approaches infinity. This enables the voltage drop at V_3 to be calculated in terms of V_S using the voltage divider principle. Using the voltage divider principle, V_1 can be calculated in terms of V_S before and after and the calibration resistor is applied:

Before the calibration resistor is applied, the voltage V_2 and V_3 is given by:

$$V_2\Big|_{Rcal=\infty} = \frac{V_s}{2} \qquad V_3\Big|_{Rcal=\infty} = \frac{V_s}{2}$$

The input impedance across strain amplifiers is very large. For example the Shinkoh DAS-407 amplifier has an input impedance of >100MΩ (Shinkoh c1980). Therefore, when the calibration resistor is not connected $V_1 = V_3$.
Thus:

$$V_1\Big|_{Rcal=\infty} = \frac{V_s}{2}$$

Now when a calibration resistor is placed across the arm of the bridge ($R_{cal} \neq \infty$), V_3 can be expressed as:

$$\begin{aligned} V_3\Big|_{Rcal\neq\infty} &= \frac{V_s(\mathrm{R_g}+\mathrm{R_w})}{(\mathrm{R_g}+\mathrm{R_w})+(\mathrm{R_g}+\mathrm{R_w})\|(\mathrm{R_w}+\mathrm{R}_{cal})} \\ &= \frac{V_s(\mathrm{R_g}+2\mathrm{R_w}+R_{cal})}{(\mathrm{R_g}+3\mathrm{R_w}+2R_{cal})} \end{aligned}$$

To simplify the following calculation we can express the above equation as simply:

$$V_3\Big|_{Rcal\neq\infty} = V_s \times K \tag{10}$$
$$\text{where } K = \frac{(\mathrm{R_g}+2\mathrm{R_w}+R_{cal})}{(\mathrm{R_g}+3\mathrm{R_w}+2R_{cal})}$$

From Figure 6, it can be seen that when the calibration resistor is placed across the active strain gauge at the Wheatstone bridge, the voltage drop between V_1 and V_3 using the voltage divider rule, can be expressed as:

$$(V_1 - V_3)\big|_{Rcal\neq\infty} = (V_s - V_3) \times \frac{R_w}{(R_w + R_{cal})}$$

Expressing the equation in terms of voltage at V_1, and substituting in equation 10 for V_3, the following expression is obtained:

$$V_1\big|_{Rcal\neq\infty} = \frac{V_s(R_w + KR_{cal})}{(R_w + R_{cal})} \tag{11}$$

The change in voltage that occurs at the output when a calibration resistor is placed across the arm of the bridge is equal to:

$$\begin{aligned}\Delta V_1 &= V_1\big|_{Rcal\neq\infty} - V_1\big|_{Rcal=\infty} \\ &= \frac{V_s(R_w + KR_{cal})}{(R_w + R_{cal})} - \frac{V_s}{2} \\ &= \frac{V_s[R_w + R_{cal}(2K-1)]}{2(R_w + R_{cal})}\end{aligned} \tag{12}$$

As the voltage at V_3 does not change shunt during calibration, the shunt calibration error for the three-wire configuration can be expressed as:

$$\begin{aligned}\%\delta_{cal} &= 1 - \frac{\Delta V_1\big|_{Rw\neq0}}{\Delta V_1\big|_{Rw=0}} \times 100 \\ &= 1 - \frac{V_s[R_w + R_{cal}(2K-1)]}{2(R_w + R_{cal})} \times \frac{(2R_g + 4R_{cal})}{V_s R_g} \times 100\end{aligned}$$

Substitute in for K:

$$\%\delta_{cal} = 1 - \frac{(R_g + 3R_w)(R_g + 2R_{cal})}{R_g(R_g + 3R_w + 2R_{cal})} \times 100 \tag{14}$$

3.6 Calculation of Shunt Calibration Error of a Quarter Bridge Three Wire Configuration

This section considers the case where a single strain gauge is placed at a remote location and a long length of three-core cable is used to connect the gauge into a Wheatstone bridge, (Figure 7). As a single cable has been used, all three lead-wires are of equal length, and thus assumed to be of equal resistance (R_w).

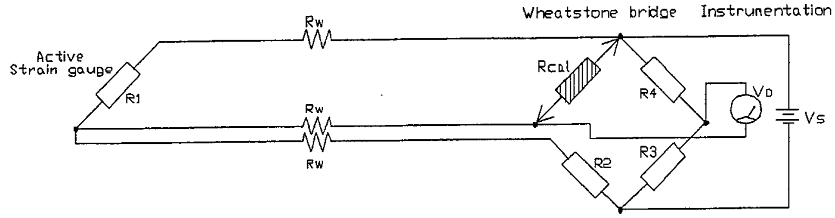

Figure 7. Single strain gauge some distance from the Wheatstone bridge location.

Comparing circuits shown in Figures 5 and 7, it can be seen that the electrical circuit for a quarter bridge using the three wire method is virtually identical to a half bridge three-wire method. Although physically a resistor is in a different location, electrically, the circuits are identical. Hence the same formulas derived for a half bridge three-wire method can be used to calculate equivalent calibration strain for the quarter bridge three-wire method.

General strain gauge theory strongly recommends that when a single gauge is placed some distance from the instrumentation, three wires (of equal length) should always be used to compensate for resistance changes in the bridge-wires due to temperature and strains induced in the wires. Therefore, a quarter bridge two-wire configuration will not be considered.

3.7 Experimental Validation of Theoretical Approach

To check that the derived equations 9 and 14, for calculating shunt calibration error were mathematically correct, experiments were conducted for both the 3 and 4 wire configurations. The wiring configurations are the same as those shown in Figures 3 and 5, which are typical wiring schematics of the Wheatstone bridge in a four wire and three wire configuration respectively. 350ohm strain gauges and 350ohm precision resistors were used in the Wheatstone bridge. The circuits were connected to Shinkoh DAS-407 strain gauge amplifiers that provided 8 volts excitation and signal amplification with the analog output being measured with a voltage meter. The shunt calibration resistor used had a nominal value of 349650Ω which equates to an equivalent calibration strain value of 500με (see Table 1). Bridge wire resistance was achieved by installing resistors of known resistance ie. 10Ω and 20Ω in series with strain gauge 1 and strain gauge 2. The calibration resistor was placed across each of the two strain gauges in the Wheatstone bridge in succession and the outputs recorded. Measurements were also undertaken for the case when there was no bridge wire resistance ie. no additional resistance in series with strain gauge 1 and strain gauge 2. The results are summarised in Table 2 together with the calculated total calibration errors and the theoretical predictions of the calibration error using equations 9 and 14.

Table 2: Experimental Shunt Calibration Results

	$R_w = 0\Omega$	$R_w = 10\Omega$	$R_w = 20\Omega$
Four Wire Method			
Shunt across gauge 1 & bridge wires	+3.093V	+2.905V	+2.750V
Shunt across gauge 2 & bridge wires	-3.087V	-2.927V	-2.732V
Average output (excluding signs)	3.090V	2.916V	2.741V
Shunt calibration error(1)	0%	5.6%	11.3%
Theoretical shunt calibration error(2)	0%	5.7%	11.4%
Three Wire Method			
Shunt across gauge 1 & bridge wires	+3.137V	+2.876V	+2.606V
Shunt across gauge 2 & bridge wires	-3.124V	-2.852V	-2.577V
Average output (excluding signs)	3.131V	2.864V	2.592V
Shunt calibration error(1)	0%	8.5%	17.2%
Theoretical shunt calibration error(3)	0%	8.57%	17.1%

Note: (1): From the above experimental results.
(2) Calculated using equation 9.
(3) Calculated using equation 14.

The experimental procedure represented extreme cases that may not be expected in most practical strain gauging exercises as lead-wire resistance of greater than 5Ω would not be expected when conducting strain gauge measurements. For example, if 22 AWG copper stranded wires were used for the signal cable between the strain gauge and the Wheatstone bridge, a 80m length would be required to produce a resistance of approximately 5Ω.

4. Strain Error Due to Long Signal Cables between the Wheatstone Bridge and Acquisition Instrumentation.

An alternative wiring configuration is to have the strain gauges and precision resistors (if required) at the same single location and connected together at that location to form a Wheatstone bridge. The instrumentation could then be a considerable distance from the Wheatstone bridge as shown in Figure 8. This eliminates bridge wire resistance, however long signal cable to the instrumentation would still be required. The bridge configuration may consist of one or two strain gauges with precision resistors completing the bridge, or it may consists of four strain gauges, or it may consist of some other resistive type transducer such as an accelerometer, load cell, pressure gauge etc.

Note that if calibration is carried out at the Wheatstone bridge, then both the attenuation and shunt calibration error will be eliminated. The shunt calibration value and hence calibrated gauge sensitivity will automatically compensate for the attenuated voltage signal when calculating strain output. However, often access to the Wheatstone bridge is not possible, and it is generally easier to calibrate at the instrumentation.

In this configuration, although negligible error will occur from the bridge-wire resistance within the Wheatstone bridge, errors will occur due to resistance in the signal cable from the instrumentation to the Wheatstone bridge. This has a two fold effect, firstly, resistance in the signal cable will cause an attenuation of the signal and secondly, resistance in the signal cable can cause an attenuation error in the shunt calibration and hence circuit sensitivity. It is important to know the magnitude of the attenuation and shunt calibration error due to the long signal cable, so these errors can be compensated for.

4.1 Attenuation Error Due to Signal Cable Resistance

Consider the situation where the Wheatstone bridge is located remote to the instrumentation and shunt calibration was not undertaken at the Wheatstone bridge and therefore attenuation error has resulted. As previously mentioned, signal strength is related to cable resistance (length), and long signal cables would result in a reduction of signal magnitude. In the following calculations it is assumed that four-core cable has been used to connect the Wheatstone bridge to the instrumentation and each of the four wires are all the same length and hence assumed to have equal resistances denoted as R_L (as opposed to R_w).

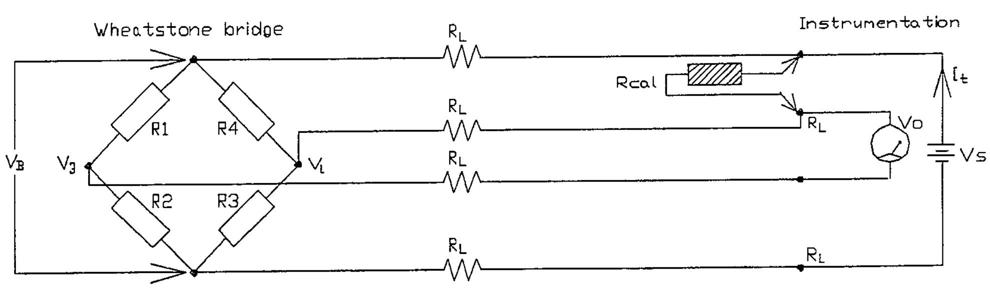

Figure 8: Schematic of Wheatstone bridge located some distance from the instrumentation.

Assuming the Wheatstone bridge is initially balanced so that R1 = R2 = R3 = R4 = R_g, the resistance across the Wheatstone bridge is equal to R_g. The voltage applied to the Wheatstone bridge will therefore be:

$$V_B\big|_{RL\neq 0} = V_s - 2I_t\big|_{RL\neq 0} \times R_L$$

As circuit current is dependent on circuit resistance:

$$I_t\big|_{RL\neq 0} = \frac{V_s}{R_T} = \frac{V_s}{R_g + 2R_L}$$

therefore

$$V_B\big|_{RL\neq 0} = V_s - \frac{2R_L V_s}{R_g + 2R_L}$$

The attenuation caused by the lead resistance in the supply wires is:

$$\%\delta_{att}(V_s) = \frac{V_B\big|_{RL=0} - V_B\big|_{RL\neq 0}}{V_B\big|_{RL=0}} \times 100$$

$$= \frac{V_S - \left(V_S - \dfrac{2R_L V_S}{R_g + 2R_L}\right)}{V_S} \times 100$$

$$= \frac{2R_L}{R_g + 2R_L} \times 100$$

As mentioned previously, the input impedance across good strain amplifiers is very large. For example the Shinkoh DAS-407 amplifier has an input impedance of >100MΩ. The resistance in the signal wires that connect the Wheatstone bridge to the amplifier have a magnitude of $2R_L$. As it is connected in series with the amplifier, the attenuation effect can be considered negligible. Therefore the above equation is also the total attenuation of the instrumentation due to resistances in the signal wires, thus:

$$\%\delta_{att} = \%\delta_{att}(V_S) = \frac{2R_L}{R_g + 2R_L} \times 100 \tag{15}$$

Murray and Miller (1992) also derived an equation for the above configuration. Murray and Miller (1992) referred to the attenuation as desensitisation factor. The equation they derived for the above configuration can be converted to a percent attenuation. When expressed as percent attenuation, it becomes identical to equation 15 above. Perry and Lissner (1955, p266) quoted an equation derived by Perino for calculating the attenuation error for the above configuration. The equation Perry and Lissner (1955) published is shown below.

$$\delta_{att} = \frac{2R_L}{R_g} \qquad \text{(Perry \& Lissner 1955)}$$

Although similar, the equation Perino derived does not provide as accurate results as equation 15, also Perry and Lissner (1955) did not quote that the equation was not an exact solution nor did they provide conditions under which it should be used.

4.2 Shunt Calibration Error due to Signal Cable Resistance

Consider the case where circumstances dictate that shunt calibration must be carried out at the instrumentation. If the Wheatstone bridge is located remote to the instrumentation then a long signal cable would be required. When a calibration

resistor is placed across the circuit as shown in Figure 8, shunt calibration errors will occur. To derive an equation for the shunt calibration error Kirchoff's voltage law using the loop procedure shall be implemented as described in Jackson (1981). As stated previously, the Wheatstone bridge is assumed to be balanced such that $R_1 = R_2 = R_3 = R_4 = R_g$. The meter resistance will also be assumed to approach infinity.

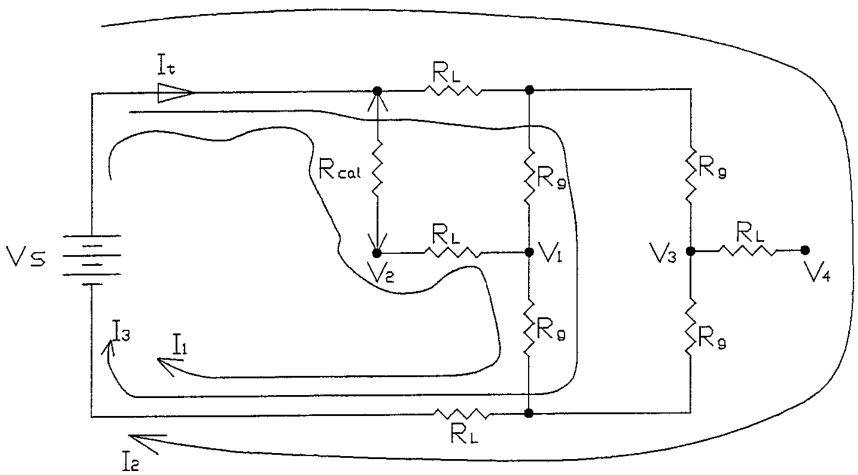

***Figure 9.** The circuit of Figure 8 re-drawn with labels and current tracing loops included*

Kirchoff's voltage law states: *"In any complete electric circuit, the algebraic sum of the source voltages must equal the algebraic sum of the voltage drops"* (Jackson 1981).
Thus using Kirchoff's voltage law, the supply voltage can be expressed in terms of the various arbitrary current paths shown in Figure 9:

loop 1: $Vs = (R_{cal} + R_L)I_1 + R_g(I_1 + I_3) + R_L(I_1 + I_2 + I_3)$ ---------(a)

loop 2: $Vs = R_L(I_2 + I_3) + 2R_gI_2 + R_L(I_1 + I_2 + I_3)$ ---------(b)

loop 3: $Vs = R_L(I_2 + I_3) + R_gI_3 + R_g(I_1 + I_3) + R_L(I_1 + I_2 + I_3)$ ---------(c)

also: $Vs = R_T(I_1 + I_2 + I_3)$ ---------(d)

where R_T = total resistance of the circuit

This provides us with four simultaneous equations with four unknowns, thus unknowns can be solved:

$$I_1 = \frac{V_S}{R_g + 3R_L + 2R_{cal}} \tag{16}$$

$$I_2 = \frac{V_S}{2(R_g + 3R_L + 2R_{cal})} + I_3 \tag{17}$$

$$I_3 = V_S\left[\frac{1}{2R_T} - \frac{3}{4(R_g + 3R_L + 2R_{cal})}\right] \tag{18}$$

$$R_T = \frac{2(6R_L^{\ 2} + 5R_g + 4R_L R_{cal} + R_g^{\ 2} + 2R_g R_{cal})}{3R_g + 8R_L + 4R_{cal}} \tag{19}$$

From Figure 9, the voltage at V_2 is equal to:

$$\begin{aligned} V_2 &= V_S - I_1 R_{cal} \\ &= \frac{V_S(R_g + 3R_L + R_{cal})}{(R_g + 3R_L + 2R_{cal})} \end{aligned} \tag{20}$$

As previously discussed, the voltage at V_4 will be the same as the voltage at V_3 as the input impedance across strain amplifiers is very large. Thus from Figure 9:

$$\begin{aligned} V_4 = V_3 &= (I_1 + I_2 + I_3)R_L + I_2 R_g \\ &= V_S\left(\frac{(R_g + 4R_L + 2R_{cal})}{2(R_g + 3R_L + 2R_{cal})}\right) \end{aligned} \tag{21}$$

The voltage output of the Wheatstone bridge at the instrumentation will be:

$$\begin{aligned} \Delta V|_{R_L \neq 0} &= V_2 - V_4 \\ &= \frac{V_S}{2}\frac{(R_g + 2R_L)}{(R_g + 3R_L + 2R_{cal})} \end{aligned} \tag{22}$$

Now if lead resistance is equal to zero, the voltage at the instrumentation, will be:

$$\begin{aligned} \Delta V|_{R_L = 0} &= V_2|_{R_L=0} - V_4|_{R_L=0} \\ &= \frac{V_S(R_g + R_{cal})}{(R_g + 2R_{cal})} - \frac{V_S}{2} \end{aligned} \tag{23}$$

Now when the calibration resistor is not in contact, it can be seen from Figure 9 that the bridge would be balanced and the voltage across the bridge would be zero:

$$\Delta V|_{Rcal=\infty} = 0 \tag{24}$$

The shunt calibration error due to signal cable is equal to:

$$\%\delta_{cal} = 1 - \frac{(\Delta V|_{Rcal\neq\infty} - \Delta V|_{Rcal=\infty})|_{RL\neq 0}}{(\Delta V|_{Rcal\neq\infty} - \Delta V|_{Rcal=\infty})|_{RL=0}} \tag{25}$$

$$=1-\frac{(R_g+2R_L)(R_g+2R_{cal})}{R_g(R_g+3R_L+2R_{cal})} \quad (26)$$

5. Simplification of Derived Equations for Shunt Calibration Error

Exact formulae were derived in section 3 and 4 for correcting errors due to shunt calibration of strain gauges when long cables are required to be used either between the gauge and the Wheatstone bridge or between the Wheatstone bridge and instrumentation. These three equations are remarkably similar and require the use of the same variables: gauge resistance, cable resistance and shunt calibration resistance. It will be demonstrated below that these equations can be simplified by applying boundary conditions thus providing simple practical equations that are sufficiently accurate for most strain gauging applications.

5.1 Simplification of Shunt Calibration error equations: for cases where the active strain gauges are located some distance from the Wheatstone bridge.

Practical strain measurement using standard foil type strain gauges generally have the following parameters:

- Strain gauges are either 120Ω, 350Ω or 1000Ω;
- A shunt calibration resistor applies an equivalent strain in the range of 500με to 10,000με;
- The bridge wire resistance is less then 10Ω.

The shunt calibration formulae derived in section 3 (equations 9 and 14) are reproduced below:

Four wire system (Figure 3):

$$\%\delta_{cal}=1-\frac{(\mathrm{R_g}+2R_w)(\mathrm{R_g}+2R_{cal})}{R_g(\mathrm{R_g}+2R_w+2R_{cal})}\times 100 \quad \text{(equation 9)}$$

Three wire system (Figure 5 or 7):

$$\%\delta_{cal}=1-\frac{(R_g+3R_w)(R_g+2R_{cal})}{R_g(R_g+3R_w+2R_{cal})}\times 100 \quad \text{(equation 14)}$$

From these two equations, it can be seen that under these practical strain measurement parameters the value of cable resistance $2R_w$ or even $3R_w$ is extremely small when compared to the sum of gauge resistance and two calibration resistance values (R_g + $2R_{cal}$), the ratio of the gauge and calibration resistance over this same

expression plus bridge wire resistances approaches 1 as shown in the expressions below:

For a four wire system:

$$\frac{(R_g + 2R_{cal})}{(R_g + 2R_w + 2R_{cal})} \approx 1 \qquad (28)$$

For a three wire system:

$$\frac{(R_g + 2R_{cal})}{(R_g + 3R_w + 2R_{cal})} \approx 1 \qquad (29)$$

Thus for all practical strain measurement applications, equations 9 and 14 can be simplified to:

For a four wire system:

$$\%\delta_{cal} = \frac{2R_w}{R_g} \times 100 \qquad (30)$$

For a three wire system:

$$\%\delta_{cal} = \frac{3R_w}{R_g} \times 100 \qquad (31)$$

To check the accuracy of these approximate solutions, consider an extreme case where cable resistance is 10Ω and shunt calibration was carried out at the Wheatstone bridge such that shunt calibration error occurs. The expected shunt calibration error that would occur have been calculated using both exact formulae (equations 9 and 14) and simplified equations 30 and 31 and is tabulated in Table 3 for 120Ω, 350Ω and 1000Ω type strain gauges for various shunt calibration resistor values (R_{cal}).

Table 3: Calculated Errors for given Strain Gauge Type and large Cable Resistances

	Equivalent micro-strain (με)	$R_g = 120\Omega$ Calibration error	$R_g = 350\Omega$ Calibration error	$R_g = 1000\Omega$ Calibration error
$R_w = 10\Omega$, four wire system				
Exact Solution	500με	16.66%	5.71%	2.00%
	1000με	16.65%	5.71%	2.00%
	3000με	16.61%	5.70%	2.00%
	10000με	16.47%	5.65%	1.99%
Simplified solution	n.a.*	16.67%	5.71%	2.00%
$R_w = 10\Omega$, three wire system				
Exact Solution	500με	24.98%	8.57%	3.00%
	1000με	24.97%	8.56%	3.00%
	3000με	24.91%	8.54%	2.99%
	10000με	24.69%	8.48%	2.97%
Simplified solution	n.a.*	25%	8.57%	3.00%

Note: * n.a. –not applicable as not required in equation, but should be within the prescribed limits of 500με to 10,000με equivalent micro-strain.

From Table 3 it can be seen that when using exact solutions, the value of the calibration resistor (R_{cal}) has very little effect on the magnitude of the calculated shunt calibration error. For example, if the bridge wire resistance is 10Ω, gauge resistance 350Ω, and a 4 wire system is used, the shunt calibration error for a 500με calibration strain is 5.71% and for 10000με calibration strain, the shunt calibration error is 5.65%, a difference of only 0.06%.

Likewise, if the calculated exact solutions of the shunt calibration error is compared to the calculated shunt calibration error using the simplified equations, there is very little difference in magnitude. In the above example the calculated shunt calibration error using the simplified equation is 5.71%. Therefore in this example the maximum possible error due to using the simplified equation instead of the exact solution is 0.06%, which could be considered negligible.

Overall it can be concluded that the results using the simplified equations compare extremely well with the exact solutions.

5.2 Simplification of Shunt Calibration error equations: for cases where the Wheatstone bridge is located some distance from the instrumentation.

The equation derived for calculating shunt calibration error for a remotely located Wheatstone bridge in relation to the instrumentation (equation 26) is reproduced below:

$$\%\delta_{cal} = 1 - \frac{(R_g + 2R_L)(R_g + 2R_{cal})}{R_g(R_g + 3R_L + 2R_{cal})}$$

As shown earlier, knowing that the shunt calibration formula derived in section 4 will be used within certain boundary conditions this formula can also be simplified. Remarkably, this equation is very similar to equation 9 if the variable R_L is substituted for R_W. Thus equation 26 can be simplified in the same manner:

$$\frac{(R_g + 2R_{cal})}{(R_g + 3R_L + 2R_{cal})} \approx 1$$

Therefore

$$\%\delta_{cal} = \frac{2R_L}{R_g} \times 100 \qquad (32)$$

Equation 32 is suitable for all practical strain gauge measurements. If a greater accuracy is required, then equation 26 should be used.

Perry and Lissner (1955 p266) quoted Perino as having derived expressions for calculating the shunt calibration error. The equation derived by Perino is identical to equation 32. Unfortunately, no calculations had been provided by Perry and Lissner, nor was it stated that it was not an exact equation.

6. Summary of Derived Equations

In this paper, a total of twelve equations have been derived for calculating attenuation and shunt calibration errors for various gauge configurations. These equations are summarised in Table 4. A comparison of each gauge configuration is also made with three different gauge resistance values and is shown in Table 5.

Table 4: Summary of exact and simplified formulae for error calculations of different wiring configurations.

Gauge Configuration	Calibration Site	Attenuation Error	Shunt Calibration Error	
			Exact solution	Simplified
1 or 2 remotely located gauges, 3 wire system.	Wheatstone bridge.	$\frac{R_w}{R_g + R_w}$	$1-\frac{(R_g+2R_w)(R_g+2R_{cal})}{R_g(R_g+3R_w+2R_{cal})}$	$\frac{3R_w}{R_g}$
2 remotely located gauges, 4 wire system	Wheatstone bridge.	$\frac{2R_w}{R_g+2R_w}$	$1-\frac{(R_g+2R_w)(R_g+2R_{cal})}{R_g(R_g+2R_w+2R_{cal})}$	$\frac{2R_w}{R_g}$
Remotely located bridge	at instrumentation	$\frac{2R_L}{R_g+2R_L}$	$1-\frac{(R_g+2R_L)(R_g+2R_{cal})}{R_g(R_g+3R_L+2R_{cal})}$	$\frac{2R_L}{R_g}$

Table 5: Comparison of the total error for different gauge configurations and gauge resistances when there is a nominal cable resistance of 5 ohm.

$R_g = 120\Omega$, R_w or $R_L = 5\Omega$	**Calibration Site**	**Attenuation Error**	**Shunt Calibration Error**	**Total Error**
1 or 2 remotely located gauges, 3 wire system	Wheatstone bridge.	4%	12.5%	16.5%
2 remotely located gauges, 4 wire system	Wheatstone bridge.	7.7%	8.3%	16.0%
Remotely located bridge	Instrumentation	7.7%	8.3%	16.0%
$R_g = 350\Omega$, R_w or $R_L = 5\Omega$				
1 or 2 remotely located gauges, 3 wire system	Wheatstone bridge.	1.4%	4.3%	5.7%
2 remotely located gauges, 4 wire system	Wheatstone bridge.	2.8%	2.9%	5.7%
Remotely located bridge	Instrumentation	2.8%	2.9%	5.7%
$R_g = 1000\Omega$, R_w or $R_L = 5\Omega$				
1 or 2 remotely located gauges, 3 wire system	Wheatstone bridge.	0.5%	1.5%	2.0%
2 remotely located gauges, 4 wire system	Wheatstone bridge.	1.0%	1.0%	2.0%
Remotely located bridge	Instrumentation	1.0%	1.0%	2.0%

7. Discussion

It can be seen from Table 5 that if 1000Ω strain gauges are used instead of 120Ω strain gauges, then there is a significant reduction in both the attenuation and shunt calibration error. Therefore for situations where the individual gauges are at some distance from the instrumentation and calibration will be carried out at the instrumentation, high resistance strain gauges should be used to minimise errors.

Dally and Riley (1984) claim that the three-wire method is better then the four wire method as it results in a lower error. However, it has been shown that under certain conditions that this is not the case. From Table 5, it can be seen that for the situation where the calibration resistor has to be placed across an arm of the Wheatstone bridge and not across the gauge, the total error for both systems are similar.

From Table 5 it can be seen that the "total error", which consists of the sum of attenuation error and shunt calibration error for the three types of wiring configurations are all similar in magnitude for a given gauge resistance. Therefore, if strain measurements are required and the gauges have to be located some distance from the acquisition instrumentation, and calibration is carried out at the Wheatstone bridge it really does not matter whether a four wire or a three wire system is used, because the overall sum of attenuation error and shunt calibration error are similar. Likewise, if calibration must be carried out at the instrumentation it really does not matter whether the Wheatstone bridge is located at the instrumentation or closer to the strain gauges as again the overall sum of attenuation error and shunt calibration error introduced due to long leads are similar.

8. Conclusions

(1) Exact equations (equations 9 & 14) were derived to calculate the shunt calibration error when a long signal cable is used to connect the gauge to the Wheatstone bridge in a four or three wire configuration.

(2) The above-mentioned equations were simplified using practical approximations. These simplified equations (equations 30 & 31) are satisfactory for all practical strain gauge applications, the residual error being less then one percent.

(3) The simplified equations were verified by experimental methods.

(4) An equation (equation 15) was derived to calculate the attenuation error when shunt calibration is carried out at the instrumentation, and a long signal cable is used between the Wheatstone bridge and instrumentation.

(5) An equation (equation 26) was derived to calculate the shunt calibration error when shunt calibration is carried out at the instrumentation, and a long signal cable is required between the Wheatstone bridge and instrumentation.

(6) The above-mentioned equation was simplified and is satisfactory for all practical strain gauge applications, the residual error being less then one percent. (Equation 32)

(7) It was mathematically demonstrated that using higher resistance strain gauges reduces attenuation and shunt calibration errors.

(8) It was shown that if strain measurements are required and the gauges have to be located some distance from the acquisition instrumentation, and shunt calibration is carried out at the Wheatstone bridge, that it really does not matter whether a four wire or a three wire system is used, because the overall sum of attenuation error and shunt calibration error are similar in magnitude.

(9) It was also shown that if shunt calibration is to be carried out at the instrumentation it really does not matter whether the Wheatstone bridge is located at the instrumentation or closer to the strain gauges as again the overall sum of attenuation error and shunt calibration error introduced due to long leads are similar in magnitude.

(10) All of the above mentioned equations are summarised in Table 4 for the reader's convenience.

9. Recommendations

When making measurements and long cables are used the following the procedure should be followed:

(i) When ever possible, undertake shunt calibration across the active strain gauge as this will completely eliminate the attenuation and shunt calibration errors.

(ii) If the above recommendation is not possible, undertake shunt calibration at the Wheatstone bridge. This will help minimise the attenuation and shunt calibration errors.

(iii) If unable to carry out a shunt calibration at the strain gauge or the Wheatstone bridge, carry out the shunt calibration at the instrumentation.

(iv) For points (ii) and (iii) measure the cable resistances so that the instrumentation engineer can make appropriate corrections using the formulae developed in this paper.

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19. ABSTRACT

In many situations where strain measurements are required, the instrumentation is located a considerable distance from the strain gauge site. This results in long cable lengths from gauge site to the instrumentation. The resistance of the signal cable can directly cause attenuation errors when acquiring strain data. It can cause further attenuation error in the strain measurement when the calibration of the strain circuit and instrumentation system is carried out using a "shunt " resistor. As these two types of errors are additive the total error can be quite large. This paper derives correction formulae to these attenuation errors for the various wiring configurations.